DOPPLER IMAGES OF RAPIDLY ROTATING A*p* STARS

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ABSTRACT. The magnetic A*p* stars are characterized by the presence of large magnetic fields which undergo periodic variations. These magnetic field variations are accompanied by spectral variations caused by the inhomogeneous distribution of elements on the stellar surface. It is believed that the magnetic field plays an important role in determining this distribution. Accurate maps of the surface distribution of elements would provide valuable probes as to the field geometry as well as provide clues to the role of the magnetic fields in the atmospheres of these stars. We have developed a new technique for mapping the local equivalent width on a stellar surface from the observed spectral line variations.

I. THE INVERSE PROBLEM

The technique employed is a modified version of the Doppler imaging technique which incorporates the maximum entropy formalism. Since this technique is described in greater detail in the paper by Vogt in this publication, we will only give a brief outline of the technique and refer the reader to Vogt's contribution.

The inverse problem (mapping local equivalent width on a star from spectral variations) is posed as a matrix equation. The image of the star is divided into n cells which are unwrapped to form an image vector **I**. Each pixel represents the local equivalent width of the star at the location of that pixel. Observed spectral lines as a function of phase are attached end-to-end to form a data vector **D** of m elements. To map from image space to data space requires a transfer matrix **R** ($n \times m$ elements) such that $\mathbf{D} = \mathbf{I}{\cdot}\mathbf{R}$

The elements of transfer matrix **R** represent the response of a datum pixel to changes in an image pixel. These elements are merely the specific line intensities computed by an LTE atmosphere divided by the equivalent width of the profile. Information about the star such as rotational velocity, inclination, as well as information about the stellar atmosphere (limb darkening, macroturbulence, *etc.*) are used in construction of the matrix **R**.

Since the problem is ill-posed, **R** cannot be inverted to solve for the image vector **I**. Instead we approximate the solution by searching in image space until a vector is found which fits the observed data to within the noise level. Since

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the number of possible image vectors consistent with the data set can be large (non-uniqueness) we impose the additional criterion that the final image is the simplest or smoothest one consistent with the observed data. The entropy of an image, which is defined as the negative of the information content, provides a convenient measure of this smoothness. The image with the least information thus has the maximum entropy. Our technique uses the algorithm developed by Drs. J. Skilling and S.F. Gull to find the image with the maximum entropy (least information) consistent with the data. The reader is referred to the article by Vogt, Penrod, and Hatzes (1987) for extensive tests conducted with the technique.

II. DATA ACQUISITION AND RESULTING IMAGES

Data sets were obtained using the 6347 Å line of Si II in γ^2 Ari and the 4824 Å line of Cr II in ϵ UMa. The data were obtained using the Lick Observatory 3 meter telescope at coudé focus and a TI 800×800 3-phase CCD detector. We have been able to achieve signal-to-noise of 300-500 per pixel and with a resolving power of 60,000 for Cr II and 51,000 for the Si II line.

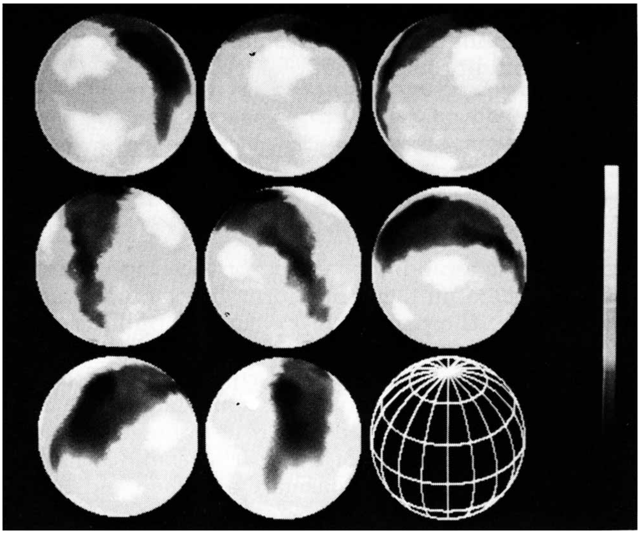

Figure 1a: Local equivalent width map of Cr II for ϵ Uma. Minimum = 70 mÅ (black), Maximum = 250 mÅ (white), Mean = 120Å (grey).

ϵ UMa is an A0pCr star with a well known period of 5.0887 days. For the modeling a v sin i of 33 km s^{-1} and an inclination of 54° were used. Figure 1a shows the resulting equivalent width map for the 4824 Å line of Cr II. In the image black represents underabundance with respect to the mean while white represents overabundance. Figure 1b shows the resulting line fits to the data as a function of phase derived from the reconstructed map (crosses represent observed data and lines represent the fit). The most prominent feature is the large arc or annulus of depleted abundance which passes by at phase 0.375 and 0.875. The plane in which this arc lies appears to miss the center of the star by about 1/5 of the stellar radius. The equivalent width inside this arc is about 70 *m*Å while the mean for the star is about 110 *m*Å. Also present are three overabundant spots situated in a circle of radius 50° about the point 0° latitude and phase 0.125 The maximum equivalent width in these spots is about 250 *m*Å.

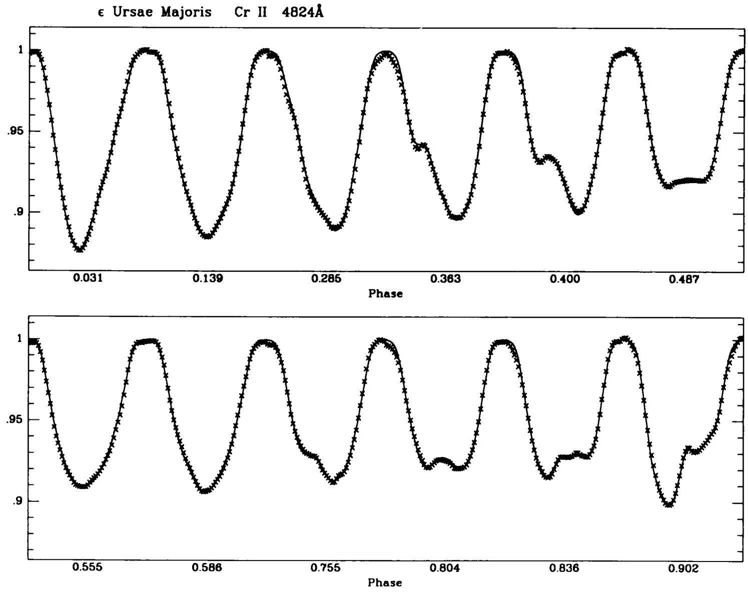

Figure 1b: Observed spectral line as a function of phase (crosses) for Cr II in ε UMa and the resulting fits (line) from the equivalent width distribution in Fig. 1

Figure 2 represents the maximum entropy solution to the local equivalent width of silicon in the star γ^2 Ari. Space does not permit showing the line fits to the data. For modeling we used a measured $v\sin i$ of 64 km s^{-1}, an inclination of 55°, and the magnetic period of 1.6093^d. There is a prominent underabundant spot 50° in latitude from the rotation axis. The equivalent width in this spot is at least a factor of 5 less than that of the mean value of 170 *m*Å across the stellar surface. This spot is coincident in longitude to the negative magnetic pole as measured by Borra and Landstreet (1980). Surrounding this spot is a non-uniform annulus of overabundance extending in radius from about 30° to 60° and centered on the underabundant spot. The equivalent width in this annulus attains a peak value of 3 times the mean. There is also a much less prominent underabundant spot at lower latitudes and 180° in longitude from the first.

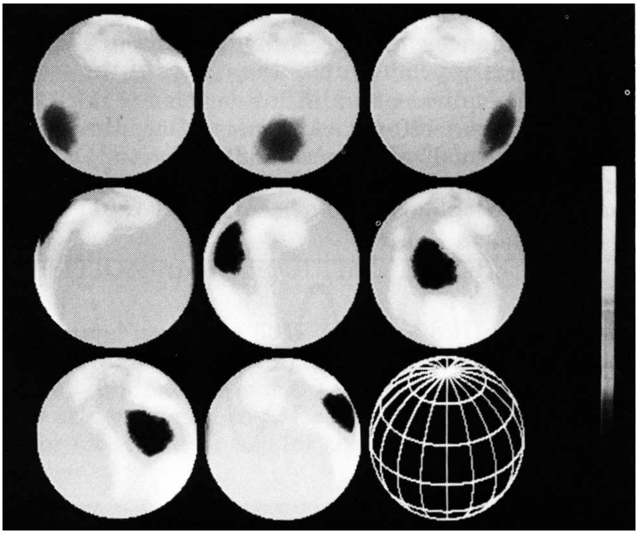

Figure 2: Equivalent width map of Si II 6347Å for γ^2 Ari. Maximum = 400Å (white), minimum = 10Å (black), mean = 170Å (grey).

III. INTERPRETATION OF THE IMAGES

The diffusion mechanism of Michaud (1970) is one explanation for the spectral variations. Work by Vauclair, Hardorp, and Peterson (1979) suggests that silicon should accumulate where fields lines are horizontal. The silicon image of γ^2 Ari seems to be consistent with this prediction. The two underabundant spots represent the two poles (obliquity angle = 50°) while the overabundant annulus must lie near the magnetic equator. This annulus is at too high a magnetic latitude to be accounted for by a pure dipole field. This can be explained by the addition of a quadrupole component or by using a dipole field whose center is displaced from the star's center toward that of the negative pole.

The interpretation of the chromium image of ϵ UMa is uncertain due to the lack of theoretical work on diffusion of chromium in the presence of magnetic fields. It is clear, however, that the great underabundant annulus most likely represents the magnetic equator. If chromium, like silicon, is depleted where the field lines are vertical, then the equivalent width map for this star suggests a quadrupole field. However, an alternate explanation is to invoke horizontal diffusion. Mégessier (1984) argued that for more evolved stars, like ϵ UMa, horizontal diffusion should become important and that the silicon band should migrate towards the magnetic poles as the star evolves. The overabundant spots may represent the enhanced abundance band which was initially at the equator, but which has migrated poleward leaving a depleted band at the equator.

IV. CONCLUSION

In conclusion we believe that this technique applied to Doppler imaging of the magnetic A*p* stars represents a powerful tool for deriving accurate local equivalent width maps on these stars. Early indications are that silicon accumulates where the field lines are horizontal and is depleted where the field lines are vertical. These results are consistent with predictions of diffusion theory and may represent the first direct observational evidence that this mechanism is present in the atmospheres of these stars.

REFERENCES

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Mégessier, C. 1984, *Astron. Astrophys.,* **138**, 267.

Michaud, G., 1970, *Astrophys. J.*, **160**, 640

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DISCUSSION

LANDSTREET:

Remark 1: Latitudes of magnetic poles determined from Balmer line Zeeman analyzer data of Borra and Landstreet are in general determined with rather low precision (errors in inclination of rotation axis, obliquity of magnetic field of $\simeq 20°$). So one can't really say that pole of equivalent width distribution coincides with magnetic pole, only that the two determination are compatible.

Remark 2: Borrar and Landstreet's measurements are not very sensitive to presence of a quadrupole component. A quadrupole/dipole ratio of $\simeq 1$ could easily be present without being obvious in the data. Thus a "quadrupolar" map of equivalent width is not contradicted by observation of a "dipolar" field.

Question: How well is inclination of distribution pole (or rotation axis) to the line of sight determined?

HATZES: The distribution of equivalent width found is almost independent of assumed inclination.

LANDSTREET: Then the inclination is not accurately determined.

HATZES: The inclination (absolute orientation) of the star is not well determined. However, the location of spots and other features (which determines the obliquity angle of the field) with respect to the rotation axis is rather insensitive to the assumed inclination of the star.

LINSKY: Please comment on the S/N and the number of obvservations per rotation period required for your mapping technique to work.

HATZES: That of course depends on the complexity of the spot configurations one is trying to reconstruct. For the Ap stars which exhibit complex distributions, I like to have $S/N \geq 300$ and 16-20 phases. For spot configurations with simple shapes good reconstructions can be made with S/N as low as 150-200 and 8 equally spaced observations.

GUSTAFSSON: Two questions: 1 - Do you restrict the "local" value of the equivalent width (apart from $W_\lambda \geq 0$) or is it a completely free parameter? and 2 - Do you limit the geometrical complexity of your solution?

HATZES: 1 - The technique assumes non-negative pixel values (i.e., $W_\lambda \geq 0$), no other restrictions are made on the equivalent width values, and 2 - The only restriction of our solution is that it is the smoothest image consistent with the data set (the maximum entropy formalism).